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Meijer, O.G.; Feigenberg, I.M.

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Bernstein's Failure to Join the Space Race: His Commentary on Tsiolkovskii's "Mechanics in Biology" (1964)

Onno G. Meijer and Iosif M. Feigenberg

October 4, 1957, the Soviet Union launched Sputnik I into orbit from Tyuratam in Turkistan. An event "with the suddenness and surprise of a Pearl Harbor and of the impact of a Hiroshima atomic explosion" (Stoiko, 1970, p. ix). Nor would this be the only time America lost to the Russians in the space race. November 3 of the same year, Sputnik II carried the dog Laika, the first living being who traveled, and died, in space. In the USA, Senator Lyndon B. Johnson lamented: "Control of space means control of the world" (quoted from Heppenheimer, 1997, p. 126), and attempts were made to speed up Wernher von Braun's launching program (Piszkiewicz, 1995; cf. Von Braun, 1968). Alas, on December 6, when the American rocket began to lift, "it seemed as if the gates of hell had opened up. Brilliant stiletto flames shot out from the side of the rocket near the engine. The vehicle agonizingly hesitated for a moment, quivered again, and in front of our unbelieving, shocked eyes, began to topple" (Halberstam, quoted from Heppenheimer, p. 127). Thus, at the UN, "Soviet delegates asked their American counterparts if the United States might wish to receive foreign aid under Moscow's program of technical assistance to backwards nations" (from Heppenheimer, p. 128).

Von Braun finally succeeded with the Explorer I on January 31, 1958, but for the Americans the agonizing wasn't over. On August 21, 1957, the Soviet Union launched an intercontinental ballistic missile (ICBM), this time carrying a dummy, but able to carry a nuclear bomb (Harford, 1997). So, the first ICBMs in the world were aimed at the USA. And then, on the morning of April 12, 1961, Yuri Gagarin shouted "*Poyekhali*" ("Let's go!") (quoted from Heppenheimer, p. 172), and was launched into space at 9:06 to fly "over America" 51 minutes later. Quite naturally, the Soviet authorities wanted to show that Russia had been ahead all the time, and historical heroes were in strong demand. The Russians didn't have to look far.

O.G. Meijer is with the Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands. I.M. Feigenberg, Emeritus Professor of Psychophysiology, can be reached at P.O. Box 11244, Gilo, 91112, Jerusalem, Israel.

Konstantin Eduardovich Tsiolkovskii (1857-1935)

Konstantin Eduardovich Tsiolkovskii was one of those creative mavericks who make the life of the historian of science such a delight (cf. Arlazorov, 1963; Glushko, 1988; Kosmodemyansky, 1956). Tsiolkovskii was born in 1857 in the village of Izhevskoye, in the same district Ryazan where Pavlov was born. When Tsiolkovskii was 9, scarlet fever rendered him deaf for the rest of his life. As a youngster he already had a knack for science, experiments, and inventions. In 1881 he independently developed the kinetic theory of gases, only to be informed by the St. Petersburg Society of Physics and Chemistry that a certain German scientist had preceded him.

In 1882 he wrote an essay titled "Mechanics in Biology," which was approved by Sechenov: "Tsiolkovskii's work proves without any doubt his talent. The author shares the opinions of the French biologists-mechanists. It is a pity, that the work is not finished and not ready for publishing" (quoted by the editor of Tsiolkovskii 1882/1964, p. 161, translated by I.M. Rubin). Tsiolkovskii was elected to the St. Petersburg Society. At the time he was completely absorbed by the possibility of space flight.

The fact that controllable space flight is possible at all results from Newton's third law (action = reaction): Produce a thrust to one side and you will move to the opposite side. This principle had been implemented before Tsiolkovskii. Nikolai Kibalchich (1853-1881) constructed a self-propelling bomb, killed Tsar Alexander II with it, wrote in prison on the feasibility of jet propulsion, and was executed (Harford, 1997). Tsiolkovskii would develop the relevant mathematics of jet propulsion. He wrote about all-metal dirigibles (Zeppelins) and experimented with airplanes that "flew well and afforded an entertaining spectacle to both children and adults" (Kosmodemyansky, 1956, p. 25). As a teacher in faraway Kaluga, he was obsessed with Jules Verne's dream of space travel. In fact, many of his ideas would be realized later: streamlined cigar-shaped rockets, liquid fuel propulsion, launching in several stages, etc.

The Tsars probably failed to grasp the scientific importance of self-propulsion. However that may be, Tsiolkovskii's creativity remained hidden, and much of his life was bitter—until the Russian Revolution, that is. After the Revolution he was recognized by the authorities and, for the first time in his life, received sufficient funding. When he died in 1935, Tsiolkovskii was famous. Thus in the 1950s the Soviet Union really had a point when they emphasized that the space race was built upon a long history in Russia. Similarly, the Germans would put Oberth in the cradle of their V2-program, and the Americans would emphasize that Goddard actually had built the things Tsiolkovskii theorized about (Schefter, 1999).

For the Russians, the need for a historical hero was even greater than for the Germans or the Americans, because of the utter secrecy of the Soviet space program. The man behind it, Sergei Pavlovich Korolev (1906-1966), remained hidden from the public. In 1940 he was released from the Kolyma (in the Gulag Archipelago, cf. Harford, 1997) to work on Stalin's space program, first as a prisoner and later working in a simple block hut at the launching site in Tyuratam. (The Khrushchev government referred to it as "Baikonur," which is 400 miles away from the actual site; cf. Heppenheimer, 1997). Of course there was no reason to be secretive about Tsiolkovskii, and in 1956 a biography was published (Kosmodemyansky, 1956), tactfully leaving out Tsiolkovskii's Polish ancestry and his religious affiliation. In 1963 another biography appeared (Arlazorov, 1963), while Tsiolkovskii's collected works were published in the 50s and 60s. Nikolai Aleksandrovich Bernstein was then asked to write a commentary on the 1964 edition of Tsiolkovskii's essay on "Mechanics in Biology" (Tsiolkovskii, 1882/1964).

Bernstein's Frustration

We know of three occasions when Bernstein wrote in the context of the space race. First he published two short newspaper articles immediately after Gagarin's flight, one in the *Pravda Ukrainy* (Bernstein, 1961a) and one in the *Molodoy Kolchoznik* (Bernstein, 1961b). Next he wrote his commentary on Tsiolkovskii's "Mechanics in Biology," published in 1964 but probably written in 1962. Finally, he wrote the introduction to Chkhaidze's dissertation in 1965 (cf. Bernstein, 1968).

The Gagarin papers are written in an authoritative style. Bernstein enjoyed educating the general public and it is clear that he knew what he was writing about. For instance: "It is often believed that 'zero gravity' starts when the cosmic ship crosses the border of the gravitational field of the earth, when it passes into the sphere, where the earth's gravity does not reach. This is completely wrong. In reality, gravity at the level of the orbit of the 'Vostok' is only a few percent smaller than that at the surface of the earth" (1961b, transl. by I.M. Rubin). And also in his introduction to Chkhaidze's dissertation, we see the master at work. Chkhaidze had studied coordination (proprioception and motor control) under changed gravity conditions, that is, in a centrifuge (high gravity) or during an airplane's nose-dive (low gravity). Under Bernstein's guidance, Chkhaidze had discovered that the human organism adapts quickly to altered gravity (cf. Kingma et al., 1999). In the introduction to the dissertation, Bernstein confidently presents his own physiology of activity (Feigenberg & Meijer, 1999; cf. Meijer & Bongaardt, 1998).

Bernstein's commentary on Tsiolkovskii's paper, however, is of a different nature. Although in and of itself certainly interesting, the structure of Bernstein's argument is not always straightforward; in several places his comments miss didactic clarity, also when compared to his other more difficult papers (such as 1935/1967). More important, the paper contains two serious mistakes (discussed in the editorial footnotes). Why does this paper, written between the Gagarin articles and Chkhaidze's dissertation, stand out so poorly?

Did Bernstein just have an off day? We don't think so, first because he was known for his extensive corrections of galley proofs, and second because he still wrote brilliant papers even when he knew he was terminally ill.

It is also unlikely that Bernstein's problem was with the paper itself (Tsiolkovskii, 1882/1964). Though nearly as long as a book, the paper is fun reading. To the modern scientist it looks like a mix between D'Arcy Thompson's *On Growth and Form* (cf. 1971/1917) and McNeill Alexander's *Exploring Biomechanics: Animals in Motion* (1992). Actually, Tsiolkovskii preceded the first of them by 35 years. In his original 1882 essay (quoted in Arlazorov, 1963, pp. 56-57), Tsiolkovskii relates the linear dimensions of animals to their strength and capacity for movement. "[The] absolute velocity of an animal in a liquid medium is a function of its linear dimensions. On average, velocity changes with the third root of the scalar" (*op cit*, transl. by I.M. Rubin), that is to say, when the linear dimensions of a fish are 8 times bigger, it will be $8^{1/3} = 2$ times faster. "Big fishes move quicker than small ones. Big *infusoria* are seen in the microscope to move quicker than small ones. The dove is quicker than the sparrow, the eagle quicker than the dove, and the sparrow quicker than winged insects" (*ibid*). In 1920 Tsiolkovskii reworked the text considerably (the above example of the fishes, for instance, is missing), but he kept his argument essentially unchanged and retained his attractive style. To Bernstein (cf. 1996/1945-46), Tsiolkovskii's essay must have sounded like music. Hence there is no reason to suspect that Tsiolkovskii's text made it difficult for him to write his commentary.

The more we discussed the awkwardness of Bernstein's Tsiolkovskii commentary, the more it became a mystery to us—until we began to analyze the context, that is, the space race. When Gagarin was the first man in orbit, Bernstein's scientific life looked much better than before (Bongaardt & Meijer, 2000). Certainly, he still didn't have a real job and the spectre of neoPavlovianism still haunted him, but he regularly presented at conferences and his publications were on the increase (one paper each year in 1958 through '60, four in '61, and six in '62; cf. Feigenberg, 1988). Moreover, he had met with Gel'fand and Tsetlin and felt recognized by them.

We began to speculate that when Bernstein wrote his Gagarin articles (1961a, 1961b), he was publicly announcing his expertise, dreaming of being directly involved in the training of cosmonauts (cf. Kozulin, 1984). Two of his group, Gurfinkel and Chkhaidze were already working with cosmonauts and we think Bernstein himself also craved participation. Nobody had an inkling as to whether people could think coherently in space, get food into the mouth, move in a coordinated fashion, etc. (Glushko, 1988), and Bernstein wanted to be part of the inner circle that dealt with such questions. Of course, permission would not come. After all, as a Jew he had been officially denounced in the *Pravda* (Feigenberg & Latash, 1996), and these were no longer the days when experts were recruited from the Gulag.

Thus, we hypothesized that in 1962 Bernstein was frustrated because he was not allowed to be directly involved in the training of cosmonauts. That hypothesis derives from 'the feeling of inner discomfort' (J.M.F.'s phrasing) that shines through in the present paper. Interviews with some of those who can know confirmed our hypothesis: In 1962 Bernstein *was* frustrated because he could not directly take part in the training of cosmonauts. Apparently his frustration had subsided by 1965 (cf. Bernstein 1965/1968), maybe because he was proud of Chkhaidze's dissertation, or because he knew he was dying and had more pressing matters on his mind. As to whether his 1962 discomfort with the space race *explains* the problems of his commentary on Tsiolkovskii's essay, we must of course let the reader decide.

Why do we want to publish this paper with all its difficulties?

First of all, coordination under changed gravity conditions remains an extremely interesting topic (cf., e.g., Gracovetsky, 1985; Kitayev-Smyk, 1977), which in our opinion still fails to get the attention it deserves. That alone, we argue, makes it worthwhile for the readers of Bernstein's Heritage to be informed about his role in the space race.

Moreover, one often learns more from mistakes than from successes (Kuhn, 1962), and we find Bernstein's mistakes in the present paper particularly enlightening: We learned from them how much he wanted to be involved in the space race.

There is an interesting story behind this minute detail of Bernstein's frustration. In the history of the space race, we see scientific integrity and creativity amidst the horrors of Stalinism (Korolev) and Nazism: Wernher von Braun had been arrested by the SS, then cooperated with the Nazis, and finally led the space program in the USA (cf. Harford, 1997). We see how the CIA pushed the space program because it wanted to play "big brother"; indeed, by now virtually everything on earth has become visible through satellites (Heppenheimer, 1997). On the other side of the race, Khrushchev brought his country to the brink of bankruptcy—and actual starvation—by his desire to be the first (Heppenheimer, 1997).

The space race began as a boys' dream in the second half of the 19th century. It led to the most frightening state of human history ever: The fact that nations can destroy, at will, any place on this earth, or even the whole earth several times over. In 1962, when spying with satellites and the use of intercontinental nuclear bombs already had become real possibilities, the space program was still so attractive that Bernstein, a man of great scientific integrity and creativity, couldn't help wanting to be part of it.

Tsiolkovskii's Essay "Mechanics in Biology"*

N.A. Bernstein
corresponding member of the Academy of Medical Sciences,
doctor of medical sciences

Most of Tsiolkovskii's creative energy was absorbed by the theory and technical implementation of cosmic flight. Still he found time to address a wide range of problems, and he attempted to build a bridge between mechanics and biology. Today we would regard such work as belonging to biophysics or biomechanics.

Tsiolkovskii wrote the first version of his essay on "Mechanics in Biology" in 1882, over 80 years ago. He then let it rest for many years and picked it up again in 1920, by which time his understanding had matured and he had acquired fame as a first class scientist. Konstantin Eduardovich reworked the text in light of his own studies of the mechanics of airplanes and Zeppelins (dirigibles). Since Tsiolkovskii's time, science and technology have progressed with tremendous speed so that some of his conclusions have since become obsolete and lost their scientific relevance. Tsiolkovskii could rely on very little if any relevant empirical knowledge. There was much he just had to assume in developing his theories,

*The paper appeared in K.E. Tsiolkovskii (1964), *Sobranie Sochinenii,* Vol. 4 (pp. 454-458). Moscow: Nauka. It was translated by I.M. Rubin and edited for clarity.

for example concerning muscle force in man, the load-bearing capacity of the skeletal system, the frequency of wing movements in insects and birds, etc.

Tsiolkovskii's essay is published here in its 1920 form. By and large, it has not lost its value, revealing Tsiolkovskii's unique talent and the gift to popularize that was so characteristic of him.

Let us imagine two geometrical bodies, or statues that are completely similar to each other, the one being bigger than the other by a linear factor P ($P = 2$, 10, 100, etc.).[1] We can say immediately that all corresponding *surface areas* of the larger object are P^2 times bigger than those of the smaller one, and corresponding *volumes* P^3 times. Assuming a homogenous composition of, for instance, marble or bronze, the *masses* of corresponding parts will also differ by P^3. That is all there is to say if we analyze two inanimate three-dimensional objects of homogenous composition that are geometrically similar to each other.

If now we start to think about living, moving[2] organisms, say two different ones with as much geometrical similarity as possible, and again a linear coefficient P, our analysis becomes much more complex and rich. We are confronted with complications right from the beginning. This we can see, for instance, if we allow forces to work on our figures. Take the simplest example. We assume that our statues represent human beings with their arms hanging down; the linear coefficient is 10. Now the hands are carrying proportional loads, different by a factor P^3, that is to say, 1000 times. But the surface areas of the cross-sections of the hands differ by not more than $P^2 = 100$ times. Consequently, the strength in the larger statue (per unit of surface area) must be 10 times bigger, and if we start to slowly increase the load for both hands, it is the hand of the larger statue that will break first. When the arm is lifted in the shoulder to a horizontal position, the torques will differ by a factor P^4, that is, 10,000 times, while the load-bearing capacities differ by P^3, or 1000 times.[3] Again, the situation is 10 times more difficult for the larger figure.

Take two homogenous cubes,[4] with a linear similarity coefficient $P = 10$, and drop them from the same height onto a hard surface. The situation will be similar to that with the statues: Mass and weight of the bigger cube differ by a factor 1000 from those of the smaller one, while the surfaces that absorb the shock differ by not more than 100. To increase the similarity, we could also drop the larger cube from a point that is 10 times higher, giving it 10 times more kinetic energy, which then would create even bigger problems.

[1]This is a typical D'Arcy Thompson problem (cf. 1917/1971). Thompson, however, did not refer to Tsiolkovskii, and one can safely assume that the two never heard of each other.

[2]In the preceding paragraph, Bernstein summarized an example from Tsiolkovskii's original text (Tsiolkovskii, 1882/1964, p. 162). Now he will proceed beyond the original by introducing movement.

[3]This is a blunder (not to be found in Tsiolkovskii's original): It should be P^2, or 100 times. Maybe Bernstein thought of the torque of shoulder muscles, but that is not in the published text. We argue that this mistake is highly unusual (and thus significant). In all his papers, Bernstein took great pleasure in presenting the right mathematics (cf. 1935/1967), and it was this tiny misprint (the third power instead of the second) that led us to formulate our hypothesis as to his frustration with the space race.

[4]This extra example adds nothing to the argument.

For such problems in theoretical mechanics, Newton already formulated the theorem of dynamical similarity in his famous book *Philosophiae Naturalis Principia Mathematica*. This theorem[5] of dynamical similarity leads to general formalisms, derived by Newton, which have been applied in recent tests with models, for instance with miniature ships in special test ponds.[6] It turns out that Newton's formalisms really contain all cases one may encounter with non-living objects. The question is whether these formalisms are also valid for all problems concerning the behavior of living organisms, that is to say, in biomechanics and biophysics. We believe Tsiolkovskii was the first in science to ask this question.

Certainly, Tsiolkovskii discussed the fundamental paradox in the relationship between load increase and increase in load-bearing capacity, as can be seen in living nature to the same degree as in the examples above. While Tsiolkovskii analyzed all the problems included in Newton's formalisms, he observed specific complications, of a different kind, as to the similarity relations in living organisms. Such complications had not been found, and could hardly have been found in inanimate mechanics.

We will present the first, maybe the most important complication of this kind.[7] Let us think of two animal species that are geometrically more or less similar, with a linear coefficient $P = 10$ as in the examples above. Instances of such pairs would be the small tree frog together with the gigantic bullfrog from Japan, or the Kiwi, a small contemporary bird species from New Zealand, together with *Dinornis moa*, a recently extinct giant bird from the same area. In each pair, lungs are used for breathing, that is to say, air-filled bags with many small interior compartments—*alveoli*—so that the usable surface area is increased just as in the radiators of central heating or in motor cylinders with air cooling.

Let us analyze two cases. In the first case, the linear dimensions of the alveoli differ by a factor $P = 10$, in accordance with the general similarity between the two species. In the second case, we view the alveoli as delicate instruments for gas exchange in breathing, their absolute dimensions being the most important factor for their functional success. In this second case, the 1000 (P^3) times bigger lung of the larger animal will have 1000 times more alveoli than the lung of the smaller animal, while the alveoli themselves have the same dimensions.

What would happen in these two cases? In the first case, the alveoli take part in the general similarity, differing by a factor 10 in their linear dimensions, while their functional surface areas differ by a factor $P^2 = 100$. In accordance with the strong assumption of perfect similarity, their number is bigger in the larger animal by a factor $P^3 = 1000$, which implies that the oxygen supply will be 10 times more difficult in the larger animal.[8] In the second case, the dimensions of

[5]It is unclear which theorem Bernstein is referring to. Tsiolkovskii writes of a "principle of similarity" (e.g., Tsiolkovskii, 1882/1964, p. 165).

[6]Reportedly, Tsiolkovskii had been the first to develop a wind tunnel (cf., e.g., Kosmodemyansky, 1956).

[7]What follows is again an example derived from Tsiolkovskii (1882/1964, pp. 163-165). Tsiolkovskii's original text reads better. The general point Tsiolkovskii is making is that microscopic relationships do not follow the same laws as macroscopic ones.

[8]This is Bernstein's second blunder, again not found in Tsiolkovskii's original. Note

the alveoli remain unchanged—as we assumed to be necessary for their functioning. Obviously, the number of such alveoli will be proportional to the volume of the lungs, that is, $P^3 = 1000$ times bigger in the larger animal. The surface area for breathing increases with the same factor so that the usable area is the same in terms of the mass of the animal, independent from the absolute dimensions.

Evidently, we have to establish the actual facts, measuring the organs and systems in order to pinpoint which road nature has chosen for their evolution. We agree with Tsiolkovskii that such examples are nothing special; on the contrary, they are typical of the differences one always finds between living organisms and Newton's simple law. Research is needed on the structure and composition of bones, the properties of the vascular system, the number and distribution of digestive *villi* in the stomach and the intestines, and finally the strictly standardized but differential configurations of elements in the construction of the liver, the kidneys, the glands, and the nervous system.

Only careful investigation will reveal which of the two extreme cases given above is closest to the actual situation of any of these organs. It is not necessary that the exponent of P be exactly equal to 2 or 3, as in the examples above; in reality it may be some fraction between 2 and 3, and some data suggest that the exponent can even be larger than 3 or smaller than 2.[9] Tsiolkovskii uses the letter H for this changeable exponent; he couldn't help but ascribe some hypothetical meaning to such exponents. In his day, experimental study, which is the only right way to approach such a problem, hadn't even begun. In our time, comparative physiology and especially the new physiology of regulation[10] has already clarified several of the enigmas of 50 years ago.

Tsiolkovskii had his own fields of interest, leading to an emphasis on particular problems. First, the energetics of the movements of living organisms: running, jumping, mountain climbing, swimming, etc.; second, the comparative mechanics of the wings of small and large organisms (insects and birds), in relation to the gigantic 'artificial' wings in birds constructed by man—airplanes.

Time and again, Tsiolkovskii gives telling examples of the dialectical transition of quantity into new quality,[11] related to changes in the relative dimensions of wings (surface area, thickness, etc.), their construction and material composition, the movement kinematics of flying, etc.

Tsiolkovskii sometimes[12] deviates from the strict, somewhat dry presentation of his calculations, equations and tables, allowing for scientific fantasies. He

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that it cannot be a simple typing error. On the other hand, if one would replace "their number" with "the mass of the body," the text would make sense again.

[9]These considerations are derived from Tsiolkovskii's text.

[10]To one of us (O.G.M.), it appears that Bernstein is exaggerating here: So far, his physiology of regulation, or for that matter physiology of activity, had not explicitly occupied itself with the problems Tsiolkovskii discusses. On the other hand, the statement is quite general, and maybe Bernstein is just referring to the growth of experimental approaches.

[11]For dialectical materialism, see Graham (1987). Its first—possibly most important—principle is that gradual quantitative changes will give rise to sudden, massive qualitative transitions (such as when water is cooled gradually and it suddenly freezes).

[12]So far, Bernstein restricted himself to discussing examples, or elaborating on

depicts what would happen if the linear dimensions of living organisms would change by $P = 10$, 100, or 1000 in one or the other direction. He describes how the increase of P leads to additional demands if the animal is to maintain an upright position in the field of gravitation because of the fact that its weight increases by a factor P^3, which would finally crush the animal. Tsiolkovskii presents an image of imaginary human beings with $P = 1/1000$, showing how different their world would look, in which respects life would be easier for them, and how problems that are trivial to us could be insurmountable for these ultra-Lilliputians.

Useless fantasies? The reader may think so, but such an opinion would reveal scientific shortsightedness. In his essay, Tsiolkovskii gives instructive examples of how such a kind of analysis is becoming more and more relevant in our contemporary situation. As a matter of fact, we cannot change the dimensions of our body by a factor 10 or 100. But very similar changes in condition can be observed on other celestial bodies of our solar system—on celestial bodies which will really become accessible to us in the near future, to begin with the nearest one, our satellite, the moon. On the surfaces of these bodies the strength of gravitation can be extremely different—from very high on Jupiter to infinitesimal as on the small asteroids. Our cosmonauts will soon meet with increased or diminished gravitation on these heavenly bodies. The effects will in many respects be similar to changes in physical dimensions on our own planet. Such effects include the stresses caused by the large acceleration in the active phase of the cosmic flight—stresses that have actually been experienced by the cosmonauts during training in the centrifuge or during actual departure into space.

After Tsiolkovskii, many scientific-utopian novels and stories were published, conveying the impressions and problems of the imaginary space traveler after landing on some cosmic object; we should never forget that Tsiolkovskii pioneered the way, not only giving vivid descriptions but also trying, for the first time, to analyze the relationships between the dimensions of a living organism and its statics and dynamics, as well as gravitation. That is his everlasting merit.[13]

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them, from the first pages of Tsiolkovskii's essay. Note that the bulk of Bernstein's commentary is concerned with these few pages only.

[13]We agree with Bernstein's concluding statement. We find his commentary interesting, but still, Tsiolkovskii's highly original (and relatively old) essay deserved more attention than Bernstein could muster. In the last two paragraphs of the commentary one can see what this is all about: the space race and the importance of biological /medical research in its context. Of course, our hypothesis concerning Bernstein's frustration cannot be proven, but we are confident it is a useful hypothesis that sheds an unusual light on a very human trait of Nikolai Aleksandrovich Bernstein.

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[14]According to a footnote by the editor on p. 161, the original 1882 manuscript was reworked by Tsiolkovskii in 1920, "not corrected, it was written anew, but its spirit did not change" (transl. by I.M. Rubin).

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